

OPTIMIZATION OF THE IRRIGATION SYSTEMS TO IMPROVE CROP PRODUCTION IN SAHELIAN ZONES USING MICROCONTROLLER SYSTEMS

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ABSTRACT

This paper is based on the use of microcontroller systems to help optimize irrigation systems in order to improve crop production in Sahelian zones. In this paper, we implement an automatic device using sensors to monitor environmental data such as soil and air conditions in real time, microcontrollers to make irrigation decisions based on these data, and modules to store data from the sensors. Analysis of this data enables informed irrigation and crop management decisions to be made. This approach enables efficient irrigation management by precisely adjusting the amount of water supplied to crops, minimizing human intervention and thus reducing costs and environmental impacts while maximizing crop yields. The results obtained in this study show that the system works well, and justify the possibility of adjusting system parameters according to crop type.

Keywords: Microcontroller, optimization, irrigation, Sahelian zones, sensors.

1. INTRODUCTION

with population growth [1]. Research has shown that as the population grows, so does the need for food. As a result, the world's need for water will increase, and water resources will gradually diminish [2]. Existing water and arable land are therefore important for the production of the agricultural products that are and will be needed to sustain the population. In Cameroon, as in other countries, there are regions such as the Sahelian zones where agriculture is underdeveloped. Sahelian zones are known to be characterized by arid and semi-arid climatic conditions, making agriculture particularly difficult in these regions. Improving the production of agricultural crops is highly dependent on the availability of water resources. Adequate water supply is therefore essential for the growth or vegetative development of crops in these areas, and irrigation would be necessary to cover crop water requirements [3].

One of the main constraints facing Sahelian farmers is the efficient management of water for crop irrigation. Inadequate irrigation can lead to reduced agricultural production and inefficient use of water resources, exacerbating already existing food security problems in these regions. Agriculture is the sector where water resources are most heavily used, not only in Cameroon but worldwide [1]. Around 70% of the world's freshwater resources are used for agricultural irrigation [4], [5]. This is why water and agricultural land must be used efficiently to slow down or even reverse the advance of the water crisis. In this context, the use of optimized irrigation systems can play a crucial role in improving crop production in Sahelian zones. Microcontroller-based systems offer promising technological solutions for optimizing irrigation according to specific crop needs and local environmental conditions. This article describes the development and design of an automated irrigation system based on microcontroller systems.

In this work, we will present in turn the state of the art on microcontroller irrigation systems and our contribution, irrigation systems and Sahelian zones, methods and materials used to carry out this work, results and discussions and end with a conclusion.

1.1. State of the art of microcontroller irrigation systems

Several studies have been done on microcontroller irrigation systems. For example, a study was carried out by ABDELALLI in 2023, on Study and creation of an Arduino-based irrigation system [6]. In his work The emphasis is on integrating sensors to optimize water use and improve irrigation efficiency. Another study was carried out on Study and construction of an automatic irrigation system [7]. This study addresses the technical aspects of the implementation of sensors and controllers. In addition, there was a master's thesis study on Study and creation of an automated irrigation system with monitoring [8]. His work focuses much more on monitoring humidity conditions and adjusting irrigation accordingly. There is also research on Study and creation of an intelligent irrigation system [3]. This work presents a system that uses algorithms to determine the best time and amount of water to provide plants. It should be noted that these works are examples and there are many others. Just like in this article, the work that has been carried out presents a growing trend towards automation and intelligence in irrigation systems, aimed at improving the efficiency and sustainability of water resources in agriculture.

This article discusses the use of microcontroller systems to optimize irrigation systems and improve agricultural production in the Sahelian regions by integrating, as in recent work, sensors to monitor soil conditions and temperature in real time. An SD module has been added to the system to record data from the sensors. The analysis of this data allows more efficient and adaptive management of irrigation. This allows us to know, for example, the characteristics of the soil such as permeability and retention capacity, so we can have an informed idea on the choice of type of crop suitable for this soil. The developed system also offers increased flexibility thanks to potentiometers to adjust the irrigation parameters according to the specificities of each crop and soil. This contribution brings significant optimization to existing irrigation systems by allowing real-time monitoring and adaptation to soil and crop conditions.

1.2. Irrigation systems and Sahelian zones

- Definitions

Irrigation is the artificial delivery of fresh water onto land for agricultural purposes, and is therefore a form of artificial precipitation used to promote the growth of agricultural crops, landscape maintenance, and the revegetation of disturbed soils in arid zones and during periods of insufficient rainfall [9]. Sahelian agriculture faces extreme climatic variability, exacerbated by climate change [10]. In Cameroon, the Sudano-Sahelian zone is located in the northern part of the country, between latitudes 8 and 13 [11], [12]. It covers an area of 100,353 km², or 21% of the national territory [13]. It comprises the administrative regions of the Far North (34,263 km²), located on the southern shores of Lake Chad, and the North (66,090 km²), which borders the Adamaoua plateau. Rainfall conditions deteriorate rapidly between the 1,200 mm of annual rainfall in the Benoué basin and the less than 500 mm of Sahelian climate on the shores of Lake Chad, concentrated between mid-June and mid-September (a concentration of rainfall over three to four months and a long dry season) [13], [14]. The precariousness of the natural environment implies adapting research proposals to the localized needs of farmers. The climate of northern Cameroon is of the Sahelo-Sudanese tropical type, characterized by two distinct seasons and wide variations in daytime temperatures according to altitude and latitude [15], [16]. The average annual temperature is 28°C over most of the region, except at high altitudes where the difference between day and night is relatively high [15]. Rainfall in the Sudano-Sahelian zone of northern Cameroon is considered one of the main factors responsible for variations in rainfed crop yields [17]. These zones face rainfall deficits almost every year. This leads to lower rainfed yields. Of all the specifications, the Far North region is the one at greatest risk from the consequences of climate change or rainfall breaks [18]. Given the seasonal instability of Sahelian zones, the programming of agricultural activities depends on the behavior of local rainfall [19], [20]. It is therefore necessary to resort to other means to solve this problem. When rainfall is insufficient, irrigation is needed to cover crop water requirements [3].

- Irrigation benefits

From a very broad perspective, population growth means that food self-sufficiency is becoming an agricultural quest in poor countries with poorly mechanized agriculture, and we need to be able to satisfy the food demand of populations [4].

In rain-fed agriculture, crops depend entirely on rainwater stored in the soil. However, the yield of this type of agriculture is only favorable in regions where the distribution of rainfall enables the soil to retain sufficient moisture during critical periods of crop growth.

In irrigated agriculture, on the other hand, the water used by cultivated plants is partially or totally supplied by man or by an autonomous system. The water is drawn from a water source, which may be a river, a lake, a dam, a pond well or an aquifer, among many others. Irrigated crops benefit not only from irrigation water, but also from natural rainfall. Irrigation is therefore a technique that provides a solution to the vagaries of rainfall. Irrigation is the artificial application of water to a cultivated surface, with the most common aim of compensating for the inadequacy of natural rainfall in relation to plant water requirements, in order to improve crop yields [21].

- Parameters influencing irrigation and the need for modern technologies

Agricultural irrigation can be influenced by various parameters and factors such as climate, rainfall, soil type, plant type and soil moisture. Crop variety, development stage, soil type and cultivation practices are all parameters to be taken into account when maximizing water use efficiency [22]. In our work, we will be focusing on soil moisture, as plants are much more dependent on this parameter [23]. Measuring soil moisture provides information on the quantity of water available in the soil. Crop water requirements vary according to type, stage of development and climatic factors [24]. It is therefore advisable to consult local agronomic resources or contact agricultural experts for more precise information on growing conditions for each crop in specific Sahelian regions. However, there is a threshold soil water content called the wilting point, at which plants wilt or become dormant due to soil water deficit. This is the lower limit of the water reserve available to plants, the upper limit being the retention capacity. It is therefore essential to take soil moisture into account when maximizing water use efficiency. This is the background to our work, the main objective of which is to design and build a low-cost, intelligent and autonomous irrigation system based on sensors and microcontrollers. The system is designed to monitor the temperature and humidity of the cultivation area in real time; irrigate the cultivated plot as the humidity level drops; and store monitoring data in real time for analysis.

2. MATERIALS AND METHODS

2.1. System concept and block diagram

The general principle of our system is to monitor environmental conditions such as soil moisture and temperature in real time, record them and automatically adjust irrigation parameters accordingly. We do this by acquiring data from sensors, processing them with a processing and control unit (the microcontroller) and then controlling crop watering. To design this system, we first propose to show its general system diagram in Figure 1.

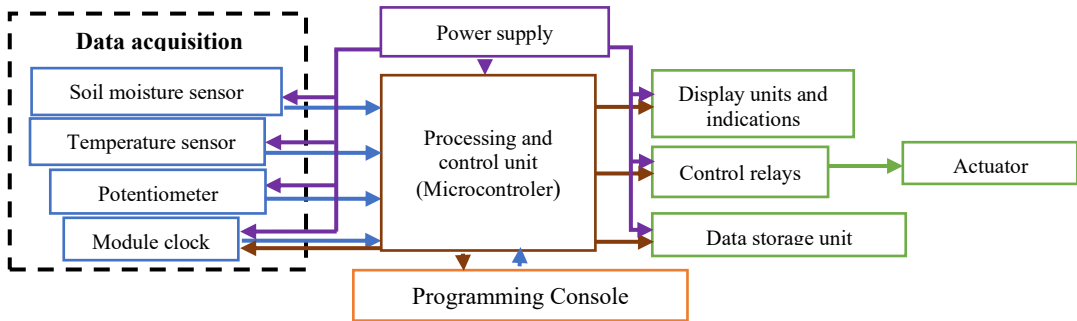


Figure 1 : General system diagram

Our general synoptic diagram has as inputs: temperature sensor, humidity sensor, clock module, potentiometers and programming console; as outputs: display unit, storage unit and actuators; a central element: a processing and control unit (microcontroller); a power supply. To realize this device, we followed the following implementation steps: selection of the microcontroller and other electronic components, wiring of the various electronic components used, programming of the microcontroller, uploading of the program to the microcontroller and testing and results of the realized device.

2.2. Microcontroller irrigation system design and development

The realization of our system is structured in two phases:

- Electronic design phase marked by the identification and selection of the electronic components used and their wiring (connection of electronic assemblies).
- Software development phase for programming the microcontroller that controls the exchange of all operations and processes, and ensures communication between the various electronic parts of the device.

- Electronic realization phase

In this phase we wire the sensors (humidity and temperature), modules (RTC module, SD module) and other electronic components (LCD, Relay, etc.). Figure 2 shows the overall Fritzing wiring diagram for our irrigation system.

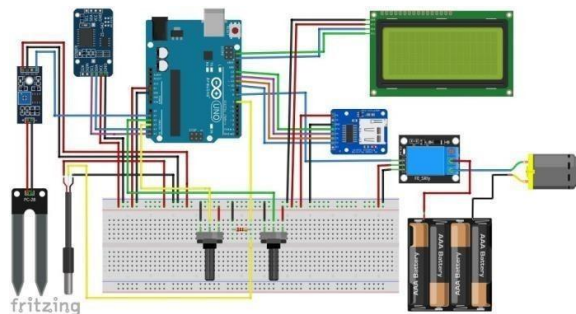


Figure 2: Overall system wiring diagram using Fritzing software

- IT implementation phase

This phase is intended for the programming (or Coding in the computer field) of our microcontroller which is the brain of the system. It is therefore an important stage in the development of our project and its structure is represented in Figure 3.

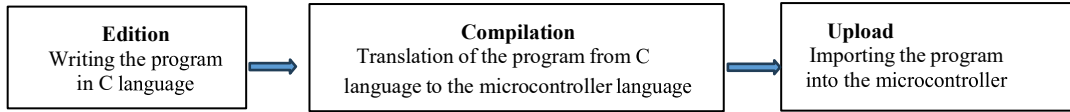


Figure 3 : Development structure for microcontroller

Editing the program: The code is written in the Arduino IDE (Integrated Development Environment) text editor using the Arduino programming language. The figure below shows us the minimal structure of this environment. It consists of a header to declare variables and constants, including libraries; a Setup() function that runs only once at the beginning of the program and contains the functions that must be executed at startup (use of input or output pins) and a Loop() function that is the main one, useful for managing real-time tasks and reading in a loop.

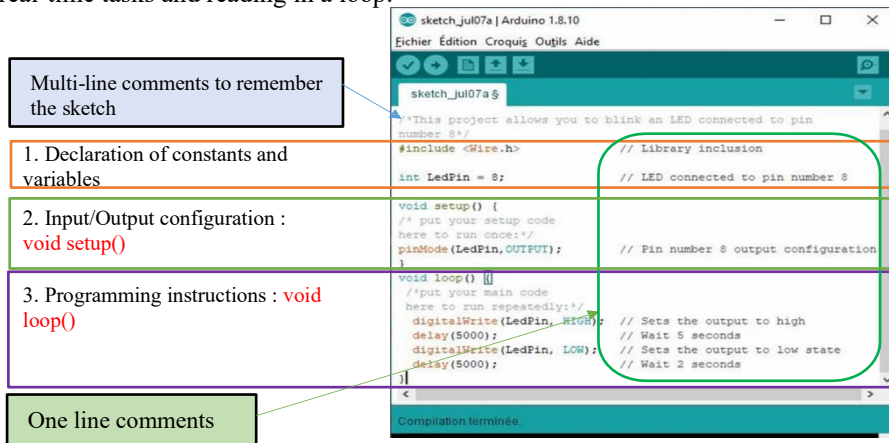


Figure 4: Minimal structure of the IDE working environment

Compilation: This translates the written code into machine code that can be executed by the Arduino microcontroller, after checking the code for syntax errors and logic problems.

Upload: The compiled code is uploaded to the Arduino microcontroller's memory. Uploading to a microcontroller board is done via a serial connection, such as a USB cable or a COM port. Once the code is correct and the connection is established, click the "Upload" button to send the compiled code to the microcontroller's memory. This step can take a few seconds to a few minutes, depending on the size of the code and the speed of the connection. Once the upload is complete, the microcontroller board can be disconnected from the computer and run on its own.

This phase is dedicated to the programming (or coding in IT terms) of our microcontroller, which is the brain of the system. This is an important stage in the development of our project, and is structured as follows: Program editing, compilation and finally Upload.

2.3. System program operation

The aim of our program is to monitor soil moisture and temperature in real time, and evaluate them in order to make decisions about whether or not to water crops. Our system also stores sensor data.

The aim of this sub-function of the system is to acquire and store data on an SD memory card for analysis. The analog pins to which the sensors are connected are read, and the data read is recorded in an array (stored locally in the Arduino board's microcontroller) and transferred to the memory card. In this case, we used a 4 GB micro SD card and the SD module as its reader. Before inserting the micro SD card into its reader, we first formatted it using the FAT32 system. Figure 5, Figure 6 and Figure 7 show, respectively, the flowchart of the data storage function and the data storage format, the flow chart of our program's operation.

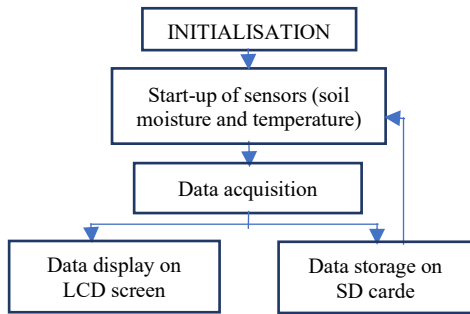
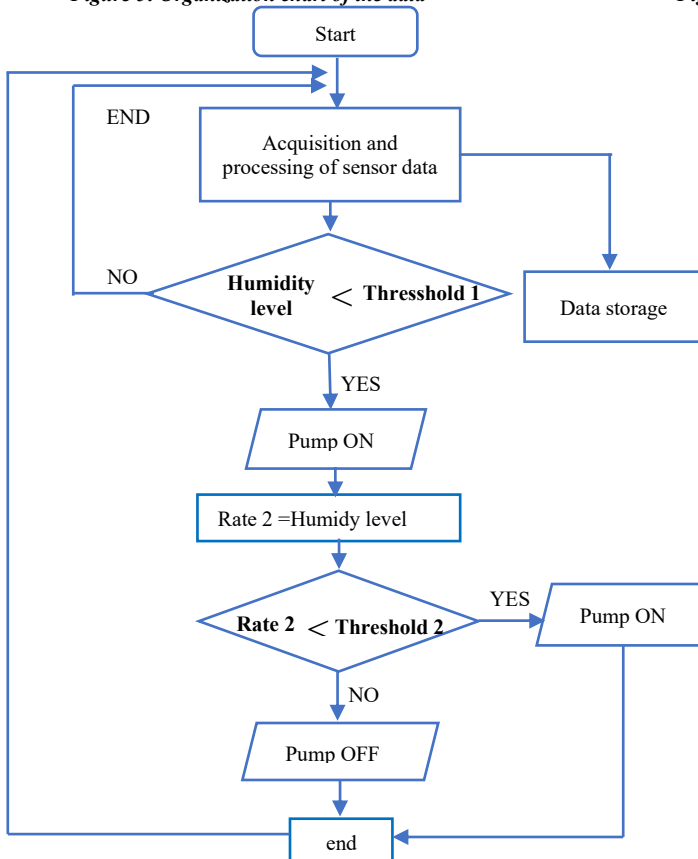


Figure 5: Organization chart of the data

DATE 1	Hours 1	Temperature 1	Soil 1
DATE 2	Hours 2	Temperature 2	Soil 2
.....			
DATE n	Hours n	Temperature n	Soil n

Figure 6 : SD data storage format



Humidity level: the soil moisture content value directly from the moisture sensor.

Threshold 1: minimum humidity level below which plants are in water deficit

Threshold 1: maximum soil moisture content for normal growth of a given crop

Rate 2: a new name assigned to the humidity level when it is below threshold 1

Pump ON: Water pump triggered, irrigation begins

Pump OFF: water pump is off, end of irrigation

Figure 7 : System flow chart

In our case, to make sure that our system's program was working properly, we carried out numerical simulations in Proteus (for the irrigation control part).

3. RESULTS AND DISCUSSION

3.1. Presentation of the system

This device is capable of monitoring environmental conditions such as soil moisture and temperature in real time, and automatically adjusting irrigation parameters accordingly. It is also capable of recording the evolution of soil moisture and temperature over time in a local database. The central element of this system, i.e. the processing and control unit, is the ATmega328P microcontroller on the Arduino Uno board. This system works by receiving data at its input, processing it to make decisions at its output. At its input we have sensors (temperature and soil moisture sensor), the RTC module and two potentiometers. The temperature sensor measures the temperature value in degrees Celsius (°C) between -55°C and +125°C. This parameter plays an important role in the choice of crop type for a given area, as each type of crop has an optimum temperature range for its normal growth. The soil moisture sensor measures the amount of water available in the soil as a percentage (%). 0% corresponds to minimum moisture and 100% to maximum moisture. This parameter is very important in our system, as it enables us to decide whether or not to water the crops. The RTC module in this device enables us to store the time set thanks to its battery in the event of a power cut. The potentiometers, which are variable resistors, enable us in this device to set the soil moisture thresholds at which the pump motor must be switched on or off. At the output of our device, we have the display, the micro water pump and the SD module. The LCD screen allows us to display values from the device input, as well as decision messages. In this device, we used a 20×4 LCD. When activated, the micro water pump supplies water from a source to the crops. It has a flow rate of 8.5 to 9L/min. The SD module stores soil temperature and humidity values. Figure 8 and Figure 9 show the final prototype of the irrigation control device before and after assembly.



Figure 8: Final prototype of the irrigation control device before assembly. Figure 9: Final prototype of the irrigation control device

3.2. Device test

For this test, we set the humidity threshold at 35%. This means that for humidity levels above this value, the micro water pump must be triggered to supply water to the crops, and must stop when the humidity level falls below this value. To vary the humidity values from its sensor, we used a water container in which the sensor was immersed and removed. During this test, the values from the sensors (temperature and soil moisture sensor) are recorded on the device's memory card (removable SD card). Figure 10 shows the test results for non-optimal and optimal conditions, while Table 1 shows the extract from the file stored on the SD card in .CSV format.



1	Date	Heure	Temp(Å°C)	Hum(%)
2	27/11/2023	15:19:8	28.06	19
3	27/11/2023	15:19:10	28	20
4	27/11/2023	15:19:12	28.06	21
5	27/11/2023	15:19:14	28.06	21
6	27/11/2023	15:19:16	28.06	21
7	27/11/2023	15:19:18	28.06	20
8	27/11/2023	15:19:20	28.06	20
9	27/11/2023	15:19:23	28.06	20
10	27/11/2023	15:19:25	28.06	20
11	27/11/2023	15:19:27	28	20
12	27/11/2023	15:19:29	28.06	20
13	27/11/2023	15:19:31	28	20
14	27/11/2023	15:19:33	28.06	20
15	27/11/2023	15:19:35	28.06	20
16	27/11/2023	15:19:37	28.06	19
17	27/11/2023	15:19:40	28.06	19
18	27/11/2023	15:19:42	28.06	19

Figure 10: Prototype test (Rate case)

Table1: Extract from the file saved on the SD Card in .CSV format

In Figure 10 above, the LCD screen displays a humidity level of $HUM = 67\%$, which is optimal for crop growth, and a temperature of $TEM = 27.12^{\circ}C$. These values were chosen arbitrarily to test just how well our system works. Analysis of the data in Table 1 gives us a better understanding of our system's operating principle. The main purpose of this device, thanks to its sensors, is to continuously monitor soil moisture and automatically adjust irrigation according to crop needs. Thanks to the data from the sensors, we can estimate the frequency and even the quantity of water supplied to the plants. To maintain humidity within the optimum growth range for each type of crop, we set two humidity thresholds (using potentiometers):

- Threshold 1: is the minimum humidity level below which plants are in water deficit. The motor must be triggered to supply water to the crops. Threshold 1 is considered here as the point soil wilt (limit value of soil moisture content below which plants wilt).
- Threshold 2: defines the maximum soil moisture content for normal crop growth. It is considered in our system as the soil's retention capacity

To better understand how our system works, we show in Figure 13 the temporal evolution of soil moisture and temperature.

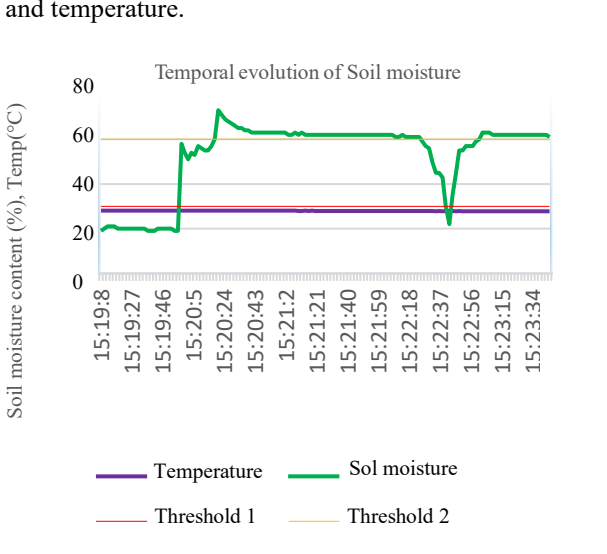


Figure 11 : Device operation test results



Figure 12: Installation of the device for humidity monitoring

In this test, we set: threshold 1 at 30% and threshold 2 at 60%. After four minutes of operation, we have the following results. During this test, the motor (mini water pump) was triggered twice:

- Firstly: triggered at 15h19min08s (Humidity = 19% < Threshold 1 = 30%), continued to motor stopped at 15h20min20s (Humidity = 60% = Threshold 2). Beyond this value, the motor remains off until the humidity level decreases and reaches its minimum value. Its operating time is: $T1 = 15h20min20s - 15h19min08s = 1min12s$.
- Second: between 15h22min46s and 15h23min7s. Its operating time is: $T2 = 15h23min07s - 15h22min46s = 21s$. So, during the test run of our device, in the four-minute interval the motor ran for the time: $T = T1 + T2 = 1min33s$. Here we see between 15:22:18 and 15:23:15 a drop in soil moisture below Threshold 1 despite the pump being open. This is because the test was done manually by inserting and removing the soil moisture sensor in the water while observing the running or non-running state of the motor.

Knowing the motor flow rate, we can also estimate the amount of water supplied by the pump to the crop during operation.

3.3. Practical test of the irrigation control device

After a number of tests that reassured us that the device was working properly, we used our device to monitor the moisture content of two soils with different textures: (clayey and sandy soil) in order to control irrigation. To do this, in addition to our own device, we have a water supply and pipesto channel the water to the soils.

- Test set-up

Figure 12 above shows the system installed to control the moisture content of the two soils. In order to control the irrigation process, it is important to install the moisture probes in the soil. Installation depends on the type of crop. The deeper the root zone, the deeper the moisture probe needs to be. These probes are very useful in irrigation management, as they provide information on the volumetric content of water in the soil. This information is useful for making many decisions and automating the watering process.

- Interpreting the results of using the device

As soon as the system is switched on, the soil moisture and field temperature values measured by the sensors are stored on the SD card. The results obtained are shown in the Figures below. Figure 13 and Figure 14 show the results for clay and sandy soils respectively.

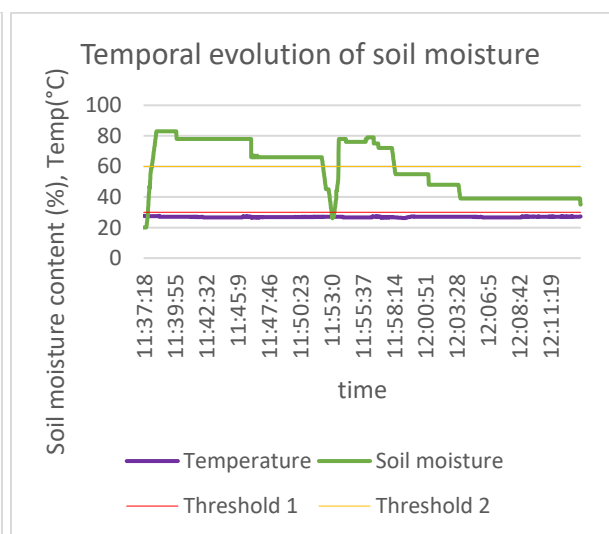
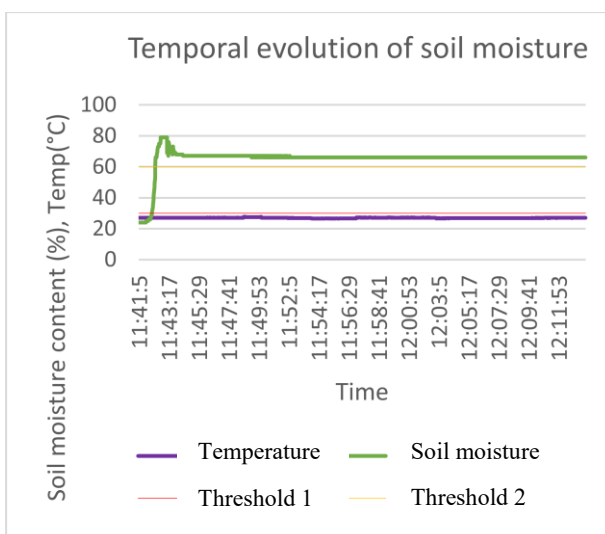


Figure 13: Results of using the device on clay soil

Figure 14: Results of using the device on sandy soil

These measurements were taken on November 27, 2023 between 11:41 a.m. and 12:13 p.m. for the Figure 14 and on November 28, 2023 between 11:37 and 12:13 for Figure 15.

- Interpretation Figure 14: during this measurement, the micro water pump was triggered once and supplied water to the clay soil between 11h41min5s (time at which the moisture sensor detected low moisture content) and 11h42min7s (time at which the sensor the optimum moisture content reached its maximum value), an operating time $T_3 = 2min2s$. After watering, this soil maintained the moisture content above its maximum normal value until the end of the soil test.

- Interpretation Figure 15: This figure shows two intervals during which the sandy soil was irrigated: the first between 11h37min18s and 11h37min50s, let's say an operating time of $T_4 = 32s$ and the second between 11h53min07s and 11h53min23s, an operating time of $T_5 = 15s$. This gives a total running time of $T_6 = 47s$.

We can see that the motor running time is longer in the case of clay soil than in the case of sandy soil. This is due to the fact that sandy soil is more permeable than clay soil, which is say water infiltrates very quickly into sandy soil than into clay soil. Sandy soils are also more prone to sudden variations in moisture content, as their retention capacity is lower.

However, moisture thresholds must be calibrated according to soil texture. To maintain the moisture content of each soil texture within its optimum crop growth range. The minimum threshold (threshold 1) must lie between the wilting point and the retention capacity corresponding to each soil texture, and the maximum threshold (threshold 2) must be higher than the retention capacity. The calibration of these moisture thresholds depends equally, and even more, on the type of crop grown. Each type of crop also needs to be grown on a specific type of soil to ensure optimum growing conditions. Maize, for example, is grown on clay and loam soils, and its optimum moisture range is between 60% and 80% in its flowering phase. We present below the results obtained from our system, calibrating the moisture thresholds for normal maize growth on clay soil.

In Figure 15, the thresholds have been chosen based on the optimum humidity range: Threshold 1 is at 60% and threshold 2 is at 80%. We note that the evolution of moisture content is maintained after watering within its optimal range for normal growth of maize in its flowering phase.

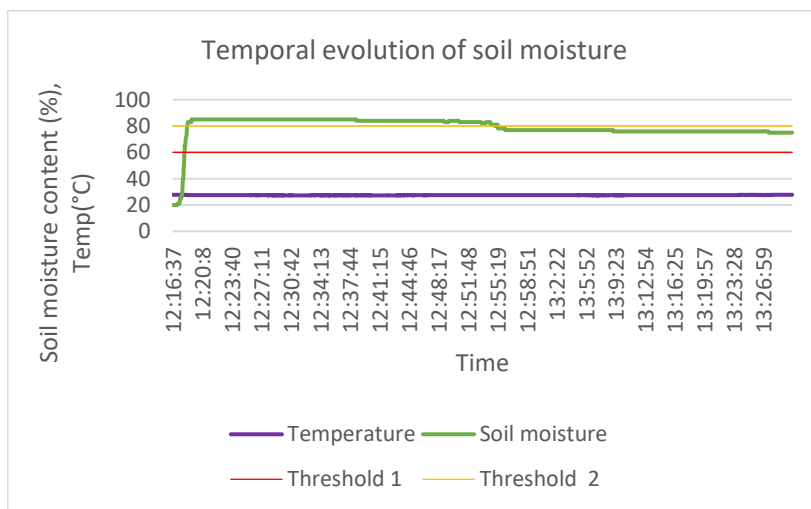


Figure 15: Device results: optimal condition for corn growth on clay soil

4. CONCLUSIONS

This work is based on the design and realization of an irrigation control device to increase agricultural production in Sahelian zones to maintain vitality. Sahelian zones are characterized by arid and semi-arid climatic conditions, making agriculture particularly difficult. Irrigation is therefore necessary to solve problems linked to water deficits caused by various factors. As water is scarce in these areas, it must be used efficiently, economically and optimally. Crop water requirements vary according to crop type and growth phase. It is also influenced by factors such as climate, temperature, humidity, rainfall and soil type. It is therefore important to carefully monitor crop water requirements and adapt accordingly. Optimizing irrigation systems is essential to ensure efficient water use and maximize crop yields. By taking into account factors such as weather, soil type, crop needs and water constraints, more precise and cost-effective irrigation strategies can be implemented. The use of advanced technologies such as soil, automated control systems based on microcontrollers can collect data in real time and adjust the quantities of water supplied to crops more precisely. This helps avoid water wastage and problems of under- or over-irrigation. In the future, we plan to optimize this device and reproduce it on printed circuit boards for commercial use. We also intend to scale it up to an industrial scale for practical use in agriculture, and use the IoT (Internet of Things) to transfer sensor data to the Internet.

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